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RIGHT-ANGLE CRASH VULNERABILITY OF MOTORCYCLES AT SIGNALIZED INTERSECTIONS: MIXED LOGIT ANALYIS

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ABSTRACT

Motorcycles are particularly vulnerable in right-angle crashes at signalized intersections. The objective of this study is to explore how variations in roadway characteristics, environmental factors, traffic factors, maneuver types, human factors as well as driver demographics influence the right-angle crash vulnerability of motorcycles at intersections. The problem is modeled using a mixed logit model with a binary choice category formulation to differentiate how an at-fault vehicle collides with a not-at-fault motorcycle in comparison to other collision types. The mixed logit formulation allows randomness in the parameters and hence takes into account the underlying heterogeneities potentially inherent in driver behavior, and other unobserved variables. A likelihood ratio test reveals that the mixed logit model is indeed better than the standard logit model. Night time riding shows a positive association with the vulnerability of motorcyclists. Moreover, motorcyclists are particularly vulnerable on single lane roads, on the curb and median lanes of multi-lane roads, and on one-way and two-way road type relative to divided-highway. Drivers who deliberately run red light as well as those who are careless towards motorcyclists especially when making turns at intersections increase the vulnerability of motorcyclists. Drivers appear more restrained when there is a passenger onboard and this has decreased the crash potential with motorcyclists. The presence of red light cameras also significantly decreases right-angle crash vulnerabilities of motorcyclists. The findings of this study would be helpful in developing more targeted countermeasures for traffic enforcement, driver/rider training and/or education, safety awareness programs to reduce the vulnerability of motorcyclists.

Key Words: Mixed Logit model; Red light camera; Environmental factors; Human factors; Motorcycle

1. INTRODUCTION

In Singapore, motorcyclists are one of the most vulnerable groups of road users. Based on crash statistics of Singapore from 1998 to 2002, the fatality and injury rates per registered vehicles are respectively about 9.5 and 5.7 times higher among motorcyclists than other vehicle drivers.

A substantial 35% of motorcycle crashes occur at signalized intersections and 59% of right-angle crashes at intersection involve motorcyclists. Considering all crashes, the crash involvement of motorcyclists as the not-at-fault party is about 43%. However, this figure is increased to 59% at signalized intersections and is even higher at 67% for right-angle crashes.

Studies [e.g., 1, 2] have suggested that the right-of-way of motorcycles at intersections is often violated: the usual crash type being a vehicle from the conflicting right-angle stream encroaching into the path of an approaching motorcycle. To examine this, Crundall et al. [3] have conducted an experiment to investigate the perception a motorcycle approaching an intersection. They concluded that drivers approaching an intersection notice motorcycles less than cars in the conflicting stream. Drivers tend to over-estimate the gap times formed by motorcycles compared to other vehicles, hence increasing the possibility of a collision [4].

Furthermore motorcyclists weaving through the traffic stream also increase their vulnerability at signalized intersections. Haque et al. [5] have reported that motorcycles are over exposed at signalized intersections because they weave through the traffic queue to accumulate near the stop-line during the red phase to facilitate an earlier discharge during the initial period of the green. Sites with more weaving opportunities, e.g, intersections with wider or exclusive right-turn lanes offer greater freedom for motorcyclists to accumulate near the stop-line during the red and thus become more exposed to crashes at the start of green.

While it may be reasonable to suggest motorcyclists are more vulnerable to right-angle crashes at intersections, it would be interesting to establish the factors that will increase such right-angle hazards. To ensure a correct appraisal of crash causation, it is necessary first to determine which parties involved in the crash are at-fault and contributing to the crash.

The objective of this study is to identify the key factors that contribute to the right-angle crash vulnerability of motorcyclists at signalized intersections. This is done by formulating a mixed logit model using the binary response variable, whether an at-fault vehicle collides with a not-at-fault motorcycle or other vehicles, to explain how roadway characteristics, environmental factors, traffic factors, maneuver types, human factors as well as driver demographics will influence the right-angle crash vulnerabilities of motorcyclists at an intersection.

2. METHODOLOGICAL APPROACH

Heterogeneity due to unobserved variables is one of the common problems in traffic safety studies. For example, variables like *dual licensed driver* (privilege to drive cars and ride motorcycles) and some other human behavioral factors are not captured in the dataset. Some [6] have suggested that dual drivers have a lower likelihood of crashes because they have better appreciation of the two transport modes and are more likely to perform the appropriate checks while driving to ensure the safety of motorcyclists around them [7]. Other unrecorded behavior-specific details such as aggressive behavior [e.g., 8] or risk-taking behavior [e.g., 9] have also been found to have a strong association with crashes. Without a proper consideration for these unobserved variables, it may not be realistic to assume the effects of the available explanatory variables can be equally applied across all individuals.

To circumvent this problem, a random variation or mixed-logit model has been developed to account for the influence of these unrecorded variables. The mixed logit model obviates three limitations of the standard logit model by accounting for random variations, unrestricted substitution patterns, and correlation in unobserved factors over time [10]. Several recent studies [e.g., 11, 12] have demonstrated the effectiveness of this approach. The mixed logit model has been successfully applied to study injury severities of highway crashes [13] and safety-belt use by the vehicle occupants [14].

2.1 Model Development

In this study, the mixed logit model is applied to model right-angle collisions between motorcycles and other vehicles. Defining the two possible outcomes as an at-fault driver/vehicle collides with (a) not-at-fault motorcycles and (b) other vehicles, in right-angle collisions at intersections, the problem can be well formulated as the binary logit model. Let T_{in} be a linear function of covariates that determine the likelihood of at-fault driver/vehicle *n*'s having the right-angle collision category *i* as,

$$T_{in} = \boldsymbol{\beta}_i' \mathbf{X}_{in} + \varepsilon_{in} \tag{1}$$

where, T_{in} is a crash-likelihood function determining the right-angle collision category (e.g., at-fault driver/vehicle collides with motorcycles or other vehicles); $\mathbf{X}_{in}$ is a vector of explanatory variables (e.g., roadway characteristics, environmental factors, traffic factors, driver's attributes, and so on); $\boldsymbol{\beta}_i$ is a vector of estimable parameters; ε_{in} is an error term. McFadden [15] has shown if ε_{in} follows a generalized extreme value distribution, the Logit formulation will be

$$P_n(i) = \frac{Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]}{\sum_I Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]} \tag{2}$$

where $P_n(i)$ is the probability that the crash-involved vehicle *n* has a particular discrete outcome category *i* from the set of all outcome categories *I*. The randomness of parameter variations across driver/vehicle types (i.e., variations in $\boldsymbol{\beta}$) are introduced by incorporating a mixed distribution in equation (2) [see 10], giving the right-angle collision probabilities:

$$P_{in} = \int \frac{Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]}{\sum_I Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]} f(\boldsymbol{\beta} \mid \varphi) d\boldsymbol{\beta} \tag{3}$$

where $f(\boldsymbol{\beta} \mid \varphi)$ is the density function of $\boldsymbol{\beta}$ with φ referring to a vector of parameters of the density function (i.e., mean and variance), and all other terms are as previously defined. For example, the density of $\boldsymbol{\beta}$ can be specified as normal with mean r and covariance S. Then the choice probability becomes

$$P_{in} = \int \frac{Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]}{\sum_I Exp[\boldsymbol{\beta}_i' \mathbf{X}_{in}]} \phi(\boldsymbol{\beta} \mid r, S) d\boldsymbol{\beta} \tag{4}$$

where $\phi(\boldsymbol{\beta} \mid r, S)$ is the normal density with mean r and covariance S. Hence the estimable parameters are r and S.

The parameter estimations under this formulation can account for individual-specific variations on the right-angle collision probabilities. The standard deviation of the $\boldsymbol{\beta}_i$ parameter vector accommodates the presence of unobservable heterogeneity in the sample population (i.e., allows for individuals within the sampled population to have different $\boldsymbol{\beta}_i$ as opposed to a single $\boldsymbol{\beta}$ representing the entire sample population). Mixed logit probabilities are the integrals of standard logit probabilities over the density of parameters. It is noteworthy to mention that some elements of the vector $\boldsymbol{\beta}$ may be fixed and some may be randomly distributed. For random parameters, as shown in equation (3), the mixed logit weights are determined by the density function $f(\boldsymbol{\beta} \mid \varphi)$.

2.2 Model Calibration and Assessment

Since the numerical integration of the mixed logit formula over the distribution of the random parameters cannot be derived analytically, the maximum likelihood estimates are usually obtained using simulations [10]. Simulation-based maximum likelihood methods are typically employed using Halton draws, which have been found to be superior to yield much more accurate approximations for numerical integrations than purely random draws [e.g., 16]. In this study, the mixed logit model has been estimated using 200 Halton draws.

Random parameters of the mixed logit model can be specified by a wide range of distributions. In this study, considerations are given to the uniform, triangular, normal and lognormal distribution. The statistical significance of the randomness of a random parameter is checked by the statistical significance of its dispersion parameter [17]. A significant parameter estimate for derived standard deviation of a random parameter would suggest the existence of heterogeneities in the parameter estimates over the sample population around the mean parameter estimate.

In order to identify the subset of explanatory variables which yields the most parsimonious model, preliminary multi-collinearity tests and backward stepwise method have been employed. To interpret the effect of coefficient estimations, both odds ratios and percentage change in predicted probabilities have been calculated. The odds ratio of a parameter is the exponential of the parameter estimate, i.e. $\exp(\beta)$ which indicates the effect of factor change in the odds of an event occurring. For the categorical variables, $\exp(\beta_a - \beta_b)$ is used to represent the odds ratios between two categories, a and b for comparison purposes. The percentage change in the predicted probabilities for each category is obtained by computing the effect of a unit change in a continuous explanatory variable from its mean or value change from 0 to 1 for a categorical variable while holding all other variables at their mean. For variables with more than two categories, the percentage change is computed based on a category change from 0 to 1 while holding other categories at 0 and all other variables at the mean. In order to account for the sampling variance of the random parameters in calculating the percentage change in predicted probabilities for those parameters, a simulation-based approach has been adopted [for details see 17].

3. DATASET FOR ANALYSIS

For this study, Singapore crash data maintained by the Singapore Traffic Police from 1998 to 2002 have been used. During this 5-year period, there were 19,415 motorcycle crashes of which 6,741 crashes occurred at intersections. As Singapore is an urbanized island country with an area of about 700 Km^2 and about 3410 km of road including expressways, arterial, collector and local roads, the context of this study is one in an urban setting.

In order to investigate the right-angle crash involvement of motorcycles, the fault of drivers/riders during collisions between motorcycles and other vehicles has been analyzed.

The definition of at-fault or not-at-fault follows that incorporated in the traffic police crash report. The at-fault drivers or riders are those who were mostly responsible for the crash occurrence and the not-at-fault drivers and riders are those who were not responsible or less responsible for the crash occurrence.

To simplify the driver's and/or rider's culpability in a crash, the analysis of this study is restricted to right-angle collisions at signalized intersections involving only two vehicles. Moreover, to get "clean" crash records, as illustrated by earlier studies [e.g., 18, 19], the following crashes have been eliminated: hit-and-crashes, crashes involving drivers/riders receiving a citation (e.g., impaired due to alcohol, intoxicated by any drug, phone using etc.), crashes where there are missing information on the fault assignment or any explanatory variable. Following this data filtering, the clean records made up about 96% of such crashes at signalized intersections. In total, 7,460 at-fault drivers/riders have been identified to be involved in two-vehicle right-angle crashes at intersections. Among these, 37% of at-fault driver/vehicles have been found to collide with not-at-fault motorcycles.

A total of 18 explanatory variables are assumed to influence the right-angle crash vulnerability of motorcycles at signalized intersections. As shown in Table 1, they include roadway characteristics, environmental factors, driver/rider attributes, vehicle factors, maneuver types, specific cause factors as well as time effects. To capture the non-linear relationship, if any, between the crash involvement and driver age, the square of the driver age has also been considered as input to the model. The majority of the variables included are categorical dummy variables that simply indicate the existence of a certain condition. Vehicles are classified into three categories: motorcycles including scooters, light vehicles including passenger cars, pick-up trucks and vans, and heavy vehicles such as buses, lorries, container trucks and trailers.

4. RESULTS AND DISCUSSIONS

The mixed logit estimates of significant variables along with crash probabilities for colliding with not-at-fault motorcycles are presented in Table 2. The likelihood ratio statistic for the model is 2245.41, which is well above the critical value at a 5% significance level. This implies that the model has a sufficient explanatory power. Moreover, the McFadden pseudo-R^2 of 0.228 also indicates a reasonable level of fit. A likelihood ratio test has also been conducted to check the appropriateness of the mixed logit model over the standard logit model in terms of model fit. The likelihood ratio statistic of 26.31, which is greater than the critical value of 14.1 with 7 degrees of freedom, ensures a better fit of the mixed logit model over the standard logit model.

An examination of Table 2 shows that all estimated parameters have plausible magnitudes and signs. Significant parameters are: *night time crash occurrence, wet surface, type of traffic, lane position, intersection type, presence of red light cameras, driver age, vehicle type, presence of passenger, maneuver of vehicles* and *specific causal factors like failing to give way, red light running*. Among the parameters the *constant term, one-way traffic type, crash at median lane, presence of red light cameras, driver age, light vehicle,* and *presence of passenger* have been found to be random across the individuals involved in right-angle crashes at signalized intersections. For all random parameters, the normal distribution has been found to yield a better statistical fit.

The odds ratio and the percentage change in predicted probability for significant variables are presented in Table 3 and the results are discussed in the following.

4.1 Night-time Crash Occurrence

Night time driving has been found to be significantly affecting the right-angle crash involvement of at-fault drivers. Its estimated parameter is fixed across the sample population as the standard deviation of this parameter distribution, when allowed to be random, is not statistically significant. Results show that night time influence increases the odds of at-fault drivers to collide with not-at-fault motorcyclists by about 16% during right-angle crash involvement at signalized intersections. Drivers often face difficulties in detecting motorcycles due to their reduced conspicuity [20] and this problem is more serious at night. Furthermore, at night vehicles may also travel at higher speeds due to less traffic and this exacerbates this hazard.

4.2 Wet Road Surface

Indicator variable *wet road surface,* as a fixed parameter, has been found to be significant in right-angle crash involvements. Results show that while the odds of right-angle collisions with motorcycles decrease by about 21% on wet road surface, the corresponding odds with other vehicles increase by about 27%. Several researchers [e.g., 21] have argued that wet pavements may be a visual deterrent for motorcyclists to exhibit any risky activity like speeding. However, the fault analysis among motorcyclists in the right-angle collisions at intersections does not show any significant difference between wet and dry road surfaces (see Table 4). Therefore, the seeming reduction in collisions with motorcycles may be due to the complementary property of the binary logit formulation, i.e., wet pavements result in an increase in right-angle crashes between at-fault vehicles and other vehicles than motorcycles. Indeed, several studies [e.g., 22] have reported that wet pavement increase the overall number of crashes. Since motorcyclists tend not to ride in the rain, their exposure is correspondingly lower than other vehicles.

4.3 Intersection Type

Intersection type has been found to be significantly associated with the right-angle crash likelihood and its parameter estimate is fixed across the samples. Relative to the four-legged intersection, the probability of right-angle collisions with motorcycles at three-legged intersections increases by about 36.7%. Ng et al. [23] have reported that red-light violations are higher for three-legged intersections than four-legged configurations. Since motorcycles are over exposed to the red runners [5], the right-angle crash vulnerability is likely to be higher at three-legged junctions.

4.4 Type of Traffic

The *type of traffic* of intersection approaches has been found to be significantly affecting right-angle crash involvements of vehicles. Using the *divided-highway* as the reference category, the likelihood of vehicles colliding with motorcycles significantly increases on approaches with *one-way* and *two-way* traffic type and the corresponding probabilities increased by 37.2% and 21.1% respectively.

The parameter for the indicator variable for *one-way traffic* has been found to be normally distributed with mean 0.270 and standard deviation 1.477. Given these estimates, the parameter is greater than zero for 57% of vehicles and less than zero for the rest 43%. This implies that at an intersection with a one-way traffic approach, 57% of vehicles are more likely to collide with motorcycles and 43% of vehicles are less likely to collide with motorcycles. One-way traffic generally offers more freedom for vehicle movements and hence drivers may be more willing to speed which may implicate exposed motorcycles on the conflicting stream. On the other hand, motorcycles discharging from one-way traffic approach are subject to fewer conflicting streams and are therefore less likely to be victims.

Two-way traffic type has been found to have a fixed parameter estimate. An approach with a two-way traffic is less channelized than an approach with the dual carriageway. In this case, the case of less channelized movements results in a hazardous condition for motorcyclists.

4.5 Lane Position

The lane position on which the right-angle crash occurs is found to be significant in the crash likelihood function. Relative to *centre lanes*, the parameter estimates for crashes on *single lane* roads have been found to be positive and fixed while crashes on the *median lane* have been found to be positive and random for determining collision category in right-angle crash involvements.

Results show that the probability of collisions with motorcycles increases by about 28% on *single-lane* roads. S*ingle-lane* roads usually have wider lanes offering greater freedom for motorcyclists to accumulate near the stop-line resulting in higher exposure and hence hazard [5]. Furthermore, there is the added opportunity of weaving and the increase in right-angle collisions with motorcycles may occur in two ways. First; the presence of motorcycles may not be clearly seen by the drivers in the conflicting stream and in the same way the view of motorcyclists in the conflicting stream may also be obstructed. This effect may be even higher if motorcycles are queuing beside a heavy vehicle on single-lane roads. Second; exposure of motorcycles is likely to be higher on single-lane roads as they accumulate in front of the queue.

Parameter estimates for right-angle collisions on the *median lane* of multilane roads have been found to vary over the sample of vehicles following a normal distribution with mean 0.227 and standard deviation 0.240, resulting in 83% of the distribution are greater than zero. On the *median lane* of multilane roads, the vulnerability of motorcyclists is higher for two reasons. First; vehicles on a *median lane* may use the unprotected right-turn phase to complete the maneuver (in Singapore, driving is on the left side of the road). Since motorcycles approaching the junction may not be well perceived [3] and their arrival times at the intersection are likely to be overestimated [4], vehicles using unprotected right-turn phase will increase the collision risk with motorcycles from the *median lane*. Second; motorcyclists are likely to use the right-turn lane to form up at stop-line even if they intend to go straight. The higher exposure of motorcyclists during the early green phase will increase the collision risk.

4.6 Presence of Red Light Camera

The parameter estimate for the indicator variable *presence of a red light camera* has been found to be normally distributed with mean -0.559 and standard deviation 1.567. It implies that when a red light camera is present, the likelihood of right-angle collisions with motorcycles decreases by about 64% while the corresponding collisions with other vehicles decreases by about 36% of driver/vehicles. In general, red light cameras are very effective in reducing right-angle collisions [e.g., 24, 25]. This study shows that given a right-angle crash, the odds of colliding with motorcycles as an at-fault party decrease by about 43% in the presence of a red light camera. Since red light cameras are very effective in curbing red light violations [e.g., 26], they will directly reduce right-angle collisions with motorcycles since motorcyclists are over-exposed to the red-runners [5]. Red light cameras tend also to restrain the discharge of motorcycles during the early period of green [27] thereby effectively reduce their exposure.

4.7 Driver Age

The *age* of at-fault vehicle drivers has been found to be significant while the *square of the driver age* has not found to be significant in determining the collision category of right-angle crash involvements. The parameter estimate of the driver age has been found to be normally distributed with mean 0.003 and standard deviation 0.015, which implies that the probability of a vehicle colliding with motorcycles increases with the age of the driver by 59% of at-fault driver/riders. The non-uniformity of this effect across vehicle drivers is captured a significant heterogeneity of driver behavior in determining the collision category since age generally have a stronger correlation with human behavioral factors (e.g., risk perception, risk-taking behaviors) which is unobserved in this study.

4.8 Vehicle Type

Among the different vehicle type, *light vehicles* and *heavy vehicles* have been found to be significant. The parameter estimate of *light vehicles* has been found to be normally distributed with mean 1.542 and standard deviation 0.969. It means 94% of *light vehicles* are more likely to collide with motorcycles with only 6% more likely to collide with other vehicles. Elsewhere [28] it was found that car drivers do not pay sufficient attention to motorcycles increasing the likelihood of they colliding with motorcycles.

The likelihood for a vehicle colliding with motorcycles at right-angle crashes is also higher for heavy vehicles with the corresponding increase of odds by 3.3 times. Other than possible driver inattentiveness to motorcycles, the relatively higher seating in heavy vehicles may create difficulties to drivers in detecting motorcycles, especially when making turning movements.

4.9 Presence of Passenger

It would be interesting to examine if presence of any passenger in at-fault vehicle would affect the crash likelihood with a not-at-fault motorcycle. The parameter estimate for the indicator variable *presence of passenger* has been found to be normally distributed with mean -4.103 and standard deviation 4.210. It gives parameter estimates being less than zero for 84% of at-fault driver/vehicles and greater than zero for the rest 16%. As there are very few cases of at-fault motorcycles crash with not-at-fault motorcycles, at-fault vehicles are therefore mainly non-motorcycles. This finding implies that for majority of drivers, with a passenger presented in the vehicle, the likelihood of colliding with motorcycles decreases, while for a small portion of drivers this likelihood tends to increase. Previous studies [e.g., 29] have shown that passengers may reduce driver's risky behavior and thus decrease crash potential while some other [e.g., 30] have shown that they distract driver's driving and increase the crash potential. In light of the above, this study shows that given a right-angle crash at intersection, the presence of passengers in at-fault vehicles also have varying effects in determining their collision category. On an average the presence of a passenger in an at-fault vehicle decreases right-angle collision probability with motorcycles by about 60.8%. This higher reduction may due to the fact that with a passenger in the vehicle, drivers generally show more cautious and safer driving behavior [31] which may be very important in detecting and perceiving motorcycles.

4.10 Maneuver of Vehicles

Maneuver of vehicles prior to the crash has also been found to be significant to be associated with right-angle collision involvements at signalized intersections. Relative to *driving ahead*, the likelihood of a vehicle colliding with motorcycles increases for *right-turning*, *left-turning* and *U-turning* movements with corresponding increase in odds of about 2.8, 3.3, and 4.1 times respectively. To get a clear understanding about right-angle collisions during different maneuvers, a matrix representing the maneuver of at-fault vehicles and not-at-fault motorcycles is derived and shown in Table 5.

One of the common types of right-angle collisions is one between a *driving-ahead* at-fault vehicle and *driving-ahead* not-at-fault motorcycles. This represents about 80.3% of the crashes among *driving-ahead* at-fault vehicles and not-at-fault motorcycles. This type of crashes commonly occurs when the at-fault drivers fail to yield to the conflicting vehicles. In this, motorcyclists are particularly vulnerable to red-running vehicles as they set off during the early green period [5]. Right-angle collisions between *driving-ahead* at-fault vehicles and *right-turning* not-at-fault motorcycles represent about 15.7%. This occurs when right-turning motorcycles take position beside other vehicles which obstruct the view of the drivers in the conflicting stream. These motorcyclists may also move off during the early green period of the protected turn, making themselves more vulnerable to red-runners.

Collisions between *right-turning* at-fault vehicles and *driving-ahead* not-at-fault motorcycles are the most frequent right-angle collisions at signalized intersections, representing about 97.7% of collisions between *right-turning* at-fault vehicles and not-at-fault motorcycles. This often occurs when vehicles turn right during the unprotected right-turn phase, misjudging the presence of an oncoming motorcycle. The view of the on-coming motorcycle may also be obstructed by queuing vehicles on the right-turn lane in the opposing traffic (see Figure 1). The on-coming motorcycle is often ignored because of its lack of conspicuity [e.g., 20], poorer perception by the right-turning driver [e.g., 3], misjudgment of motorcycle speed [e.g., 4]. Furthermore, it has also been reported that the right-turning drivers experience higher workload resulting in a higher probability of making mistakes in judgment [32].

Left-turning and *U-turning* at-fault vehicles are also likely than those *driving ahead* to collide with not-at-fault motorcycles. Such crashes arise because these movements depend very much on the driver yielding to the motorcycles which is often not conspicuous or misjudged.

4.11 Specific Cause

The variable indicating specific cause of the crash has been found to be statistically significant with fixed parameter estimates. Using *other causes* (e.g., improper lane changing, speeding etc.) as the reference category, the significant specific causes of at-fault drivers include *turning without due care*, *failing to give-way*, *improper lookout of vehicles in the traffic stream*, *red-light running*, giving corresponding increase in probabilities of about 41.8%, 37.2%, 24.4%, and 44.4% respectively. These causes highlight the earlier discussion on the factors influencing right-angle collisions with not-at-fault motorcycles. They reinforce the findings that motorcycles are less conspicuous and drivers often misjudge the presence and actions of motorcyclists..

5. IMPLICATIONS

This study has identified several significant factors influencing the vulnerability of motorcyclists at right-angle collisions at signalized intersections. These findings will be helpful in designing corrective program related to traffic enforcement, driver/rider education, training etc. They suggest the need to develop safety campaigns or awareness programs to make riders more aware of these potentially dangerous situations in which they more likely to be victims.

From the findings related to night crashes, a good follow up corrective program is to encourage motorcyclists to increase their visibility by wearing reflective clothes and using brighter headlights. Using highly reflective markings in motorcycles and helmets may also increase their visibility at night. In Singapore, while it is mandatory for motorcyclists to use the headlight during the daytime and helmet use for riders and pillion passengers throughout their trip, the there is currently no legislation to insist the use of reflective clothing or retro reflective signs in motorcycles and helmets. It is important to develop legislation on this.

The findings related to the use of red light cameras at intersections shows that they are effective in reducing the vulnerability of motorcyclists. Since motorcyclists are also more prone to serious injuries in the event of a crash, they should be accorded higher priority for the safety improvements. Hence sites with high motorcycle traffic should be given preference in red-light camera installation. In deciding whether to install these cameras, the cost-benefit analysis should specially take into account the impact of motorcycle vulnerabilities.

The study also shows motorcyclists are more vulnerable when making specific movements including weaving and right-turning. Rider education and training programs should highlight these specific movements and encounter types. The current rider training programs focus mainly on motorcycle handling with only limited lessons on queuing at junctions. This may be because it is generally more difficult to expose the trainees to different traffic situations at junctions. This difficulty may be overcome with the use of riding simulators with various scenarios of conflicting encounters. These training should also be supplemented with an on-going awareness program to remind riders of their own vulnerabilities to specific situations on the road.

Among right-angle collisions, the most prevailing is one between right-turning vehicles and straight-going motorcycles especially during the unprotected right-turn phase. The provision of protected right-turn phases at sites with high motorcycle traffic may be an effective intervention measure. Furthermore, at sites with high motorcycle presence, implementing a system of actuated signal control to give protected right-turn phase may be a cost-effective countermeasure. Due to its size and perhaps different waiting position from other vehicles, motorcycles may not activate the right-turn phase as readily and this possibility should be carefully investigated. Another potential countermeasure is to develop an intelligent system of electronic warning message signs to alert drivers of any on-coming motorcycles.

Besides educating the motorcyclists regarding their vulnerabilities, drivers should also be made aware of their likelihood to make mistakes in judging the presence and actions of motorcycles. Defensive driving should incorporate more lessons on giving the benefit of doubt to motorcycles, especially when they are least expected. On the other hand, motorcyclists should be taught to be more disciplined in taking up proper positions while queuing at the intersection to enhance their visibility to other road users. Another novel idea is to encourage motorcyclists to flash their headlight during approaching towards a junction.

6. CONCLUSION

Using the superior methodology found in mixed logit modeling, this study has demonstrated that there are unique factors which affect motorcycle safety at signalized intersections.

While some findings related to motorcyclist vulnerability are reinforcement of previous research, this study also brought in new insights regarding why motorcyclists can be victims in encounters at signalized intersections. These findings ought to result in greater impetus to tackle the hazards faced by motorcyclists with targeted measures including awareness programs to educate both motorcyclists and drivers on the specific motorcycle vulnerabilities. The new insights gained from this study should also prompt the authorities to establish more targeted legislation and enforcement measures to improve motorcycle safety.

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TABLE 1 Summary Statistics of Explanatory Variables Included in the Model

Explanatory Variables	Description of Variables	Mean	St. Dev
Time Trend	Month of Crash (Assuming that January 1998=1 to December 2002=60)	31.329	16.942
Weekend Indicator	If crash is on weekend (Friday 2000 to Sunday 2400)=1, otherwise=0	0.323	0.468
Night time Indicator	If crash between 1900 to 0700=1, otherwise=0	0.437	0.496
Wet Road Surface	If crash is on wet road surface=1, otherwise=0	0.098	0.297
Intersection Type	If crash is on three-legged intersection =1, on four-legged intersection =0	0.430	0.495
Type of Traffic			
One-way	If crash is on one-way road=1, otherwise=0	0.070	0.255
Two-way	If crash is on two-way road=1, otherwise=0	0.247	0.431
Divided-highway*	If crash is on divided highway=1, otherwise=0	0.683	0.465
Lane Position			
Single Lane	If crash is on single lane=1, otherwise=0	0.066	0.249
Curb Lane	If crash is on curb lane=1, otherwise=0	0.230	0.421
Median Lane	If crash is on right lane=1, otherwise=0	0.203	0.402
Centre Lane*	If crash is on centre lanes=1, otherwise=0	0.501	0.500
Speed Limit			
40 Km/h	If speed limit 40 Km/h=1, otherwise=0	0.018	0.133
50 Km/h*	If speed limit 50 Km/h=1, otherwise=0	0.950	0.219
70 Km/h	If speed limit 70 Km/h=1, otherwise=0	0.029	0.169
>70 Km/h	If speed limit >70 Km/h=1, otherwise=0	0.003	0.053
Presence of Red Light Camera	If camera exists at crash location=1, otherwise=0	0.109	0.311
Age	Continuous	39.095	12.702
Gender	If driver/rider is male=1, otherwise=0	0.875	0.330
Driver/Rider Race			
Chinese*	If driver/rider is Chinese=1, otherwise=0	0.792	0.406
Malay	If driver/rider is Malay=1, otherwise=0	0.111	0.314
Others	If driver/rider is of other race=1, otherwise=0	0.096	0.295
Vehicle Type			
Motorcycle*	If vehicle is a motorcycle=1, otherwise=0	0.191	0.393
Light Vehicle	If vehicle is a light vehicle=1, otherwise=0	0.690	0.463
Heavy Vehicle	If vehicle is a heavy vehicle=1, otherwise=0	0.119	0.324
Presence of Passenger	If a passenger present in the vehicle during the crash=1, otherwise=0	0.118	0.323
Registration[1]	If vehicle registered other than Singapore=1, otherwise=0	0.056	0.231
Headlight	If headlight is on during crash=1, otherwise=0	0.596	0.491

Maneuver of Vehicle				
	Driving Ahead*	If vehicle is driving ahead=1, otherwise=0	0.327	0.469
	Right-turning	If vehicle is right turning=1, otherwise=0	0.569	0.495
	Left-turning	If vehicle is left turning=1, otherwise=0	0.044	0.206
	U-turning	If vehicle is U turning=1, otherwise=0	0.030	0.170
	Others	If vehicle is doing other maneuver=1, otherwise=0	0.031	0.172
Specific Cause				
	Care	If driver/rider is turning without due to care to other vehicles=1, otherwise=0	0.243	0.429
	Give way	If driver/rider fails to give way to other vehicles =1, otherwise=0	0.266	0.442
	Lookout	If driver/rider fails to ensure a proper lookout of vehicles in the traffic stream=1, otherwise=0	0.276	0.447
	Red-light Running	If driver/rider runs the red prior to the crash=1, otherwise=0	0.161	0.368
	Others*	For other reasons=1, otherwise=0	0.053	0.225

* Reference Category for Categorical independent variables

[1] A large number of vehicles from Malaysia enter into Singapore for work everyday because of geographical proximity

TABLE 2 Mixed Logit Estimates of Significant Variables for Colliding with Not-at-fault Motorcycles at Right-angle Collisions

Explanatory Variable	**Parameter Estimate**	**Standard Deviation**	**z-statistic**
Constant (st. dev. of parameter dist.)	-3.208 (0.404)	0.167 (0.032)	-19.20 (12.46)
Night time indicator, fixed parameter	0.149	0.046	3.21
Wet Road Surface, fixed parameter	-0.237	0.076	-3.13
Intersection Type	0.444	0.048	9.20
Type of Traffic			
One-way (st. dev. of parameter dist.)	0.270 (1.477)	0.102 (0.150)	2.64 (9.83)
Two-way, fixed parameter	0.273	0.057	4.80
Lane Position			
Single Lane, fixed parameter	0.359	0.103	3.51
Curb Lane, fixed parameter	0.081	0.056	1.46
Median Lane (st. dev. of parameter dist.)	0.227 (0.240)	0.059 (0.070)	3.82 (3.44)
Presence of Red Light Camera (st. dev. of parameter dist.)	-0.559 (1.567)	0.090 (0.136)	-6.25 (11.55)
Age (st. dev. of parameter dist.)	0.003 (0.015)	0.002 (0.001)	2.18 (18.18)
Vehicle Type			
Light Vehicle (st. dev. of parameter dist.)	1.542 (0.969)	0.085 (0.039)	18.11 (19.58)
Heavy Vehicle, fixed parameter	1.192	0.100	11.90
Presence of Passenger (st. dev. of parameter dist.)	-4.103 (4.210)	0.481 (487)	-8.54 (8.64)
Maneuver of Vehicle			
Right-turning, fixed parameter	1.047	0.072	14.59
Left-turning, fixed parameter	1.198	0.118	10.17
U-turning, fixed parameter	1.411	0.138	10.22
Others, fixed parameter	1.046	0.143	7.32
Specific Cause			
Care, fixed parameter	0.472	0.122	3.88
Give way, fixed parameter	0.424	0.121	3.51
Lookout, fixed parameter	0.288	.121	2.39
Red-light Running, fixed parameter	0.498	0.143	-3.48
Number of observations		7460	
Log-likelihood at zero		-4919.415	
Log-likelihood at convergence		-3796.709	
Log-likelihood at convergence without random parameters		-3809.864	
Pseduo-R^2		0.228	
LR chi-square		2245.41 (28df)	
p-value for LR chi-square		<0.0001	
LR chi-square for random parameters		26.31 (7df)	
p-value for LR chi-square with random parameters		0.0004	

TABLE 3 Odds Ratio and Marginal Effects of Significant Variables

Explanatory Variable	Odds Ratio	%Change in probability for Collision with	
		Motorcycles	Other Vehicles
Night time indicator	1.160	11.12	-4.24
Wet Road Surface	0.789	-15.87	6.61
Intersection Type	1.560	36.71	-12.34
Type of Traffic			
One-way	1.310	37.21	-13.89
Two-way	1.314	21.09	-7.87
Lane Position			
Single Lane	1.432	28.20	-10.50
Curb Lane	1.085	6.04	-2.25
Median Lane	1.255	18.02	-6.71
Presence of Red Light Camera	0.572	-10.51	4.55
Age	1.003	0.41	-0.17
Vehicle Type			
Light Vehicle	4.674	252.46	-30.75
Heavy Vehicle	3.292	163.61	-19.93
Presence of Passenger	0.017	-60.75	40.17
Maneuver of Vehicle			
Right-turning	2.848	118.28	-23.37
Left-turning	3.315	139.87	-27.63
U-turning	4.101	171.31	-33.84
Others	2.847	118.22	-23.36
Specific Cause			
Care	1.603	41.77	-11.54
Give way	1.529	37.17	-10.27
Lookout	1.334	24.40	-6.74
Red-light Running	1.645	44.36	-12.25

TABLE 4 Motorcyclists' Fault in Right-angle Crashes by Road Surface Condition

Road Surface Condition	Motorcyclist		Odds Ratio	Chi-square	p-value
	At-fault	Not-at-fault			
Wet	117	247	0.935	0.325	0.569
Dry	1,306	2,579	Reference		

TABLE 5 Right-Angle Collisions Matrix between At-fault Motor-vehicles and Not-at-fault Motorcycles by Maneuver Type

Maneuver of at-fault motor-vehicle	**Maneuver of Not-at-fault Motorcycles**				
	Driving Ahead	Right-turning	Left-turning	U-turning	Others
Driving Ahead	80.33% (241)*	15.67% (47)	1.33% (4)	0.33% (1)	2.33% (7)
Right-turning	97.71% (2,004)	1.37% (28)	0.1% (2)	0% (0)	0.83% (17)
Left-turning	98.47% (193)	0% (0)	1.02% (2)	0% (0)	0.51% (1)
U-turning	97.74% (130)	0.75% (1)	0.75% (1)	0% (0)	0.75% (1)
Others	93.1% (81)	1.15% (1)	0% (0)	0% (0)	5.75% (5)

* Parentheses refer to frequency

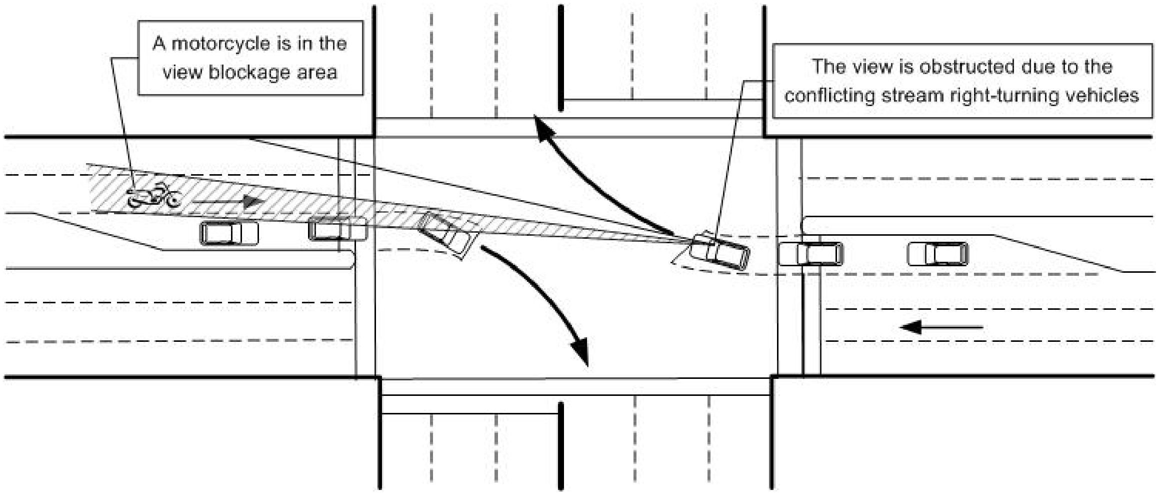

FIGURE 1 A typical right-turning with the unprotected right-turn phase